

COMPARISON OF MAGNETIC FLUX DISTRIBUTION BETWEEN A CORONAL HOLE AND A QUIET REGION

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ABSTRACT

Employing Big Bear Solar Observatory (BBSO) deep magnetograms and $H\alpha$ images in a quiet region and a coronal hole, observed on September 14 and 16, 2004, respectively, we have explored the magnetic flux emergence, disappearance and distribution in the two regions. The following results are obtained: (1) The evolution of magnetic flux in the quiet region is much faster than that in the coronal hole, as the flux appeared in the form of ephemeral regions in the quiet region is 4.3 times as large as that in the coronal hole, and the flux disappeared in the form of flux cancellation, 2.9 times as fast as in the coronal hole. (2) More magnetic elements with opposite polarities in the quiet region are connected by arch filaments, estimating from magnetograms and $H\alpha$ images. (3) We measured the magnetic flux of about 1000 magnetic elements in each observing region. The flux distribution of network and intranetwork (IN) elements is similar in both polarities in the quiet region. For network fields in the coronal hole, the number of negative elements is much more than that of positive elements. However for the IN fields, the number of positive elements is much more than that of negative elements. (4) In the coronal hole, the fraction of negative flux change obviously with different threshold flux density. 73% of the magnetic fields with flux density larger than 2 Gauss is negative polarity, and 95% of the magnetic fields is negative, if we only measure the fields with their flux density larger than 20 Gauss. Our results display that in a coronal hole, stronger fields is occupied by one predominant polarity; however the majority of weaker fields, occupied by the other polarity.

Subject headings: Sun: chromosphere — Sun: magnetic fields — Sun: UV radiation

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1. INTRODUCTION

Small-scale magnetic elements on the Sun have been under intensive investigation for many years. They occur predominantly in the quiet sun region, especially along the borders of the supergranular cells where the chromospheric network can be visualized in the filtergrams of chromospheric lines(need line examples). Based on their locations and morphology(am I right here?), small-scale magnetic fields in the quiet sun region can be classified in three categories, namely, network (Leighton, Noyes, & Simon 1962), intranetwork (IN) (Livingston & Harvey 1975) and ephemeral regions (Harvey & Martin 1973).

Based on the polarimetry results using the fourier transform spectrometer (reference) at Kitt Peak, Arizona, together with sophisticated modelling, the Zürich group and its collaborators were able to establish hydrodynamic pictures for small scale magnetic flux tubes in plages and network of the quiet Sun. Extensive reviews on these results can be found in Solanki (1993) and Stenflo (1994). The first Stokes-V measurement using line ratio technique (reference) was made by Keller et al. (1994), who placed an upper limit on the intrinsic strength of intranetwork (IN) fields to be 1000 gauss or 500 gauss with 68% probability. Also using infrared spectro-polarimetry, Lin (1995) found that the typical field strength of IN fields are around 500 gauss. Sánchez Almeida et al. (1996) suggested that the IN fields are highly irregular over optically thin scales (layers?). Kneer & Stolpe (1996) presented an image in which small-scale magnetic elements possess substructure and are dynamical, with gas flows and magnetic field strength varying in space and time. Meunier, Solanki, & Livingston (1998) obtained the fraction of magnetic flux in a weak field form, i.e. with magnitude lower than 1,000 Gauss intrinsic strength in the quiet Sun. However, Socas-Navarro & Lites (2004) presented an evidence of strong ($\sim 1,700$ Gauss) and weak (< 500 Gauss) fields coexisting within the resolution element at both network and IN regions, and there was a larger fractional area of weak fields in the convective upflows than in the downflows.

(I guess more specific contents of each paper referred here need to be mentioned.)In parallel, by means of video magnetograph observations, especially based on time sequences of deep magnetograms obtained at Big Bear Solar Observatory (BBSO), much progress was made in network and IN morphology dynamics and some quantitative aspects, such as flux distribution of quiet-Sun magnetic elements (Wang 1995); mean horizontal velocity fields of IN and network fields by using the local correlation tracking technique (Wang et al. 1996); lifetime of IN elements (Zhang et al. 1998a); motion patterns and evolution of IN and network magnetic fields (Zhang et al. 1998b,c).

On the other hand, coronal holes are cool, low density regions, which can be observed at both low latitudes region and polar region of the Sun (Chiuderi Drago et al. 1999). They were first observed on X-ray plates by Underwood & Muney (1967), on EUV line spectroheliograms by Reeves & Parkinson (1970) and in white light by Altshuler & Perry (1972). The magnetic fields within a coronal hole region are usually dominated by one polarity, and thus the field lines in the

upper atmosphere are open to the interplanetary region (Bohlin 1977), generating high-speed solar wind that can lead to geomagnetic storms (Krieger & Timothy 1973). According to the location and lifetime, there are three categories of coronal holes: polar, non-polar and transient coronal holes. Polar coronal holes have long lifetimes (about 8 years)(reference). Non-polar coronal holes are usually associated with remnants of active regions and may persist for many solar rotations. Transient coronal holes are associated with eruptive events, such as filament eruptions and coronal mass ejections (CMEs) and have lifetimes of several days (Harvey & Recely 2002). Also, low-latitude coronal holes may show quasi-rigid rotation and it has been suggested that magnetic reconnection must occur continuously at the boundary in order to maintain the integrity of coronal hole (Kahler & Hudson 2002).

In order to answer some of the key questions in solar and stellar physics, such as the coronal heating and solar wind acceleration, we need to study and understand the small-scale magnetic activity both in coronal holes and in quiet regions. In this paper, we focus on two topics: a) the dipole flux emergence and flux disappearance in a coronal hole and a quiet region; b) the distribution of magnetic flux with both polarities in the two observing regions, using BBSO long-integration magnetograms. Base on these discussion, we will finally propose a physical model for the characteristics of the magnetic fields in these two regions.

2. OBSERVATIONS AND ANALYSIS

A sequence of collaborative observations were carried out from 13th to 18th in September 2004 by BBSO team and the Transition Region and Coronal Explorer (TRACE) team. We selected the observation data obtained on 14th and 16th for this study due to the completeness and the quality of the data. The observation area on 14th was a quiet region centered at N9°W13°, and on 16th, was a coronal hole at N31°E14°. $H\alpha$ line center and Ca II K line images were taken with two Kodak CCD cameras mounted on the 25 cm refractor with 90 s cadence. Images at $H\alpha \pm 0.60 \text{ \AA}$ were taken with an Orbiting Solar Laboratory (OSL) CCD camera mounted on the 65 cm telescope with a 30 s cadence, which have FOV $210'' \times 210''$, and an image scale of $0''.4 \text{ pixel}^{-1}$. The magnetogram was obtained using the digital vector magnetograph (DVMG) system mounted on the 25 cm refractor with a cadence of 90 s, FOV $300'' \times 300''$, and an image scale of $0''.60 \text{ pixel}^{-1}$. The DVMG system uses a Zeiss filter, and a 12-bit digital camera. The averaged noise level of these magnetogram is 2 Gauss. In Figure. 1, the magnetogram of the quiet region (upper panel) and the coronal hole (lower panel) are shown together for comparison.

The high-resolution UV observation was obtained from TRACE satellite (Handy et al. 1999), which are used in this paper as a reference for identifying fine structures and the dynamics of the corona and transition region. The 1600 \AA images used in this study have spatial resolution of $1''$,

temporal resolution of 40 s, and field-of-view of $250'' \times 250''$.

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3. RESULTS

3.1. MAGNETIC FLUX EMERGENCE AND DISAPPEARANCE

In the co-spatial field-of-view (about 200×200 square arcsec) among BBSO magnetograms, $H\alpha$ filtergrams, and TRACE 1600 Å images, We identified 30 pairs of ephemeral regions (ERs) in the quiet region on September 14, 2004 during the 7-hour observations. The mean flux of an ER is 8.1×10^{18} Mx. 7 of the 30 ERs are connected by arch filaments, seeing from $H\alpha$ images. Figure 2 shows the evolution of an ER (see the two arrows on the magnetogram at 20:36 UT). $H\alpha+0.60$ Å observations display that the two elements of the ER always undergo downflows (Doppler blueshifts, black patches indicated by two arrows on the $H\alpha+0.60$ Å image at 20:35 UT). Just as the appearance of the ER, UV bright points (the arrows on the UV image at 20:41 UT) also appear at the feet of the two magnetic elements, seen from TRACE 1600 Å images. As the ER growing, it is more clearly that the two elements belonging to the ER are connected by an arch filament (denoted by dotted lines in two $H\alpha$ filtergrams at 22:49 and 22:50 UT) and the UV bright points become larger and larger, then each point splits into several ones(e.g., the arrows in the bottom panel).

For the coronal hole, although the observational time and the field-of-view are the same as that of the quiet region, we can only track 17 pairs of ERs, and one of the 17 ERs is connected by an arch filament. The mean flux of an ER is 3.4×10^{18} Mx, much smaller than that in the quiet region. Figure 3 displays the flux versus flux density of all the ERs in the quiet region and the coronal hole. It shows that there is a similar flux and flux density distributions of the ERs in the two regions. However in the coronal hole, the number of the ERs in a higher flux density and a larger flux range is much smaller than that in the quiet region, and the total flux of all the 17 ERs is 5.8×10^{19} Mx, only the 23% as large as the flux (2.5×10^{20} Mx) of the 30 ERs in the quiet region. This implies that the evolution of magnetic flux in the coronal hole is much slower than that in the quiet region. We find from Figure 3 that only if the flux is larger than 5.0×10^{18} Mx and flux density higher than 20 Gauss then the ERs are observed to be connected by arch filament systems. Considering ERs as closed magnetic loops, we can estimate the flux density of these loops ranges from 6 to 40 Gauss in the quiet region, and from 6 to 22 Gauss in the coronal hole.

Another parameter which can also represent the magnetic evolution rate is magnetic flux disappearance. The disappearance is mainly due to the cancellation of opposite polarity elements.

If an magnetic element meets with another of opposite polarity, they can cancel each other. Under this condition, the total flux decreases. In the quiet region, about 1.7×10^{20} Mx (2.1×10^{20} Mx) positive flux (negative flux) disappear by the cancellation in the 7-hour observations. In the coronal hole, the amount of the disappeared flux is about 3.5×10^{19} Mx (9.6×10^{19} Mx) for positive flux (negative flux), one third as large as that in the quiet region.

3.2. MAGNETIC FLUX DISTRIBUTION

It is always suggested that coronal holes lie within a unipolar magnetic region. However the solar magnetic field is never strictly unipolar. We have no knowledge about the IN flux distribution in coronal holes, although Wang (1995) presented flux distribution of IN and network magnetic elements in a quiet region. Here we study the flux distribution in both polarities in the coronal hole, and compare with the quiet region. Three criteria are used to separate the IN elements from the network elements (Wang 1995). For each region, about 1000 magnetic elements are identified and measured. The statistics are listed in Table 1. Figure 4 presents flux distributions of all the measured magnetic elements. The bin size for IN data points is 5.0×10^{16} Mx, and 5.0×10^{17} Mx for network. In the quiet region, the flux distribution of IN and network elements is similar in both polarities. For network fields in the coronal hole, there is no positive elements in the range where magnetic flux larger than 4.0×10^{18} Mx. However for the IN fields, the number of positive elements is much larger than that of negative elements. In other words, in this coronal hole the stronger field is occupied by one predominant polarity; and the majority of weaker fields, occupied by the opposite polarity.

Now we measure the magnetic flux in both polarities instead of the individual elements in the two regions. Figure 5 shows the variation of magnetic flux versus threshold flux density in the field-of-view of the magnetograms in Figure 1. As the threshold flux density increases from 2 Gauss (near noise level) to 30 Gauss, the flux in both polarities decreases homologically in the quiet region (see the upper panel of Figure 5). In the coronal hole, the positive flux decreases more quickly than the negative flux with increasing threshold flux density, as shown in the middle panel of Figure 5. The bottom panel presents the fraction of the negative flux to the total (negative plus positive) flux. In the coronal hole, 73% of the magnetic fields with flux density larger than 2 Gauss is negative, and 95% of the magnetic fields is negative, if we only measure the fields with their flux density larger than 20 Gauss, the noise level of a typical magnetogram. Comparing to the coronal hole, we conclude that the fraction in the quiet region changes more gently. This result further confirms the conclusion that in the coronal hole, stronger field is occupied by one predominant polarity, and weaker fields, occupied by the opposite polarity with a large margin.

4. DISCUSSION

In this paper, we find that the dipole flux emergence rate in the quiet region exceeds that in the coronal hole by thrice. A similar result was presented by Abramenko, Fisk, & Yurchyshyn (2006) who used the MDI data with the detection limit for the magnetic flux density being 17 Gauss, and only looked at the much larger ERs. This result is consistent with the model of Fisk (2005). In his model, the regions where the rate of emergence of new flux is a local minimum, open flux accumulates to form coronal holes. The flux disappearance rate in the quiet region is also more than twice larger than that in the coronal hole. Therefore, the transformation rate from magnetic energy to heat and kinetic energy is lower in the coronal hole.

H α observations show that many H α threads connect dipolar magnetic elements in the quiet region. However in the coronal hole, almost all the H α threads appear as jets in shape. This means that near the atmospheric level where H α line forms, the magnetic fields in coronal hole are almost opened. Magnetic field measurement indicates that in the quiet region the flux distribution of the IN fields is similar to that of the network fields, and the opposite polarity fluxes are basically balanced. In the coronal hole, the number of negative network elements is much more dominant than that of positive elements. However for the IN fields, the number of positive elements is much more than that of negative elements. We search some other high resolution magnetic fields data to check the reliability of the results shown in Figure 5. The BBSO deep magnetograms of June 4, 1992 provided unprecedented observations for a quiet sun. The variation of magnetic flux versus threshold flux density is similar as that in the quiet region observed on Sep. 14, 2004. In other two coronal hole regions which located near the solar disk, observed on September 17, 2004 and October 11, 2005, the magnetic flux variation is also followed the tendency as shown in the middle panel of Figure 5. This implies that the different magnetic flux distribution between the coronal hole and the quiet region is somehow common, not just a random case.

The observed scenario for the magnetic structures in the two regions can be schematically shown in Figure 6. Dotted lines represent the magnetic field lines which have no H α counterparts. The loops in the coronal hole are on average flatter than in the quiet region. High and long closed loops are extremely rare, whereas short and low-lying loops are almost as abundant in coronal holes as in the quiet Sun (Wiegelmann & Solanki 2004). The observations may hint a physical picture that some IN flux, preferentially close to the cell boundary, may be topologically connected to the network field (Zhang et al. 1999). It is necessary to point out that IN flux of the same sign of the surrounding network is more likely to be counted as network flux. Somehow IN flux of the same sign as the surrounding network is destroyed more rapidly either by merging with the network or diffusing. Furthermore, IN flux of the opposite polarity rises in more concentrated form and so it is easier to be detected.

Tu et al. (2005) established that the fast solar wind starts flowing out of a corona hole at

heights above the photosphere between 5,000 and 20,000 kilometers in magnetic funnels. Our work shows that in the coronal hole on Sep. 16, 2004, most of closed magnetic loops are lower than 5,000 kilometers, and open magnetic field with one polarity fill the space above 5,000 kilometers, where fast solar wind originates from. Flux cancellation, or a lower magnetic reconnection in the photosphere and lower chromosphere may only take place below the atmospheric level of 5,000 kilometers, not in the location where the fast solar wind starts. This implies that the release of magnetic energy and the origin of fast solar wind happen at different atmospheric level.

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Fig. 1.— BBSO magnetograms in a quiet region (upper) and a coronal hole (lower). The field of view is 200×200 square arcsec. A box in the magnetogram of the quiet sun outlines a region of ephemeral flux (see Fig. 2).

TABLE 1
Flux distribution in the two regions in both polarities

	Network		IN	
	Positive	Negative	Positive	Negative
The quiet sun				
Number	102	116	376	383
Total flux(10^{20} Mx)	4.1	–6.4	2.2	–2.8
Flux imbalance		–0.22		–0.12
Mean flux (10^{18} Mx)	4.02	–5.52	0.59	–0.73
Flux density (Gauss)	21.3	–25.8	4.1	–4.6
The coronal hole				
Number	59	153	540	342
Total flux (10^{20} Mx)	1.1	–9.8	2.7	–1.6
Flux imbalance		–0.80	0.26	
Mean flux (10^{18} Mx)	1.86	–6.41	0.50	–0.47
Flux density (Gauss)	15.2	–29.5	4.2	–4.3

Fig. 2.— A pair of ephemeral region in the quiet region on September 14, 2004. From left column to right column: BBSO magnetograms, $H\alpha - 0.6 \text{ \AA}$ images, $H\alpha + 0.6 \text{ \AA}$ images, $H\alpha$ Dopplergrams, and *TRACE* 1600 \AA images. The field of view is about 30×30 square arcsec. Arrows and dotted lines are described in the text.

Fig. 3.— *Upper*: Flux vs flux density of 30 pairs of ERs in the quiet region. *Lower*: The same as upper panel but for 17 pairs of ERs in the coronal hole. Vertical dotted lines show the flux density of 20 Gauss, and horizontal lines, flux of 5×10^{18} Mx. Heavy symbols represent these ephemeral regions that are connected by arch filament systems.

Fig. 4.— *Upper*: Flux distributions of positive and negative elements in the quiet region (upper) and the coronal hole (lower). Vertical dotted lines represent the magnetic flux of 10^{18} Mx which separates the IN elements from the network elements.

Fig. 1.— Variation of magnetic flux vs threshold flux density in the field-of-view of magnetograms in Fig. 1 in the quiet region (*upper*) and the coronal hole (*middle*). The lower panel displays the flux fraction of the negative flux relative to the total flux.

Fig. 6.— Schematic of the magnetic structure of two regions. *Upper*: The quiet sun. *Lower*: The coronal hole. Solid lines indicate the magnetic field lines which have H α counterparts, e.g. the closed lines versus arch filaments, and opened lines, macrospicules. The dotted lines show field lines which have no H α counterparts.